



Heat exchanger operation in the externally heated air valve engine with separated settling chambers



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ABSTRACT

The crucial role in the externally heated air valve engine is played by its heat exchangers which work in a closed cycle. These are: a heater and a cooler and they are subject to a numerical analysis in the paper. Both of them are equipped with fixed volumes that are separate settling chambers causing that heat exchangers behave as almost stationary recuperators and analysis of the stationary behaviour is the main goal of the paper. Power and efficiency of the engine must be not lower than their averaged values for the same engine working in unsteady conditions. The results of calculations confirm such a statement. The pressure drop in the exchanger is another natural phenomenon presented. It has been overcome by use of additional blowers and the use of them is an additional focus of the presented analysis. A separation of settling chambers and additional blowers is a novelty in the paper. There is also a pre-heater applied in the engine which does not differ from well-known heat exchangers met in energy generation devices. The main objective of the paper is to find the behaviour of the engine model under stationary conditions of the heat exchangers and compare it with the non-stationary ones.

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1. Introduction

The air engine with external heating referred to as the EHVE (Externally Heated Valve Engine) is presented in Ref. [1] and its comparisons to the helium Stirling engine are to be found in Ref. [2]. Air powered engines like the one discussed here, which works in the modified Joule cycle are still developed – theoretically, in a smaller scale, see Lontsi et al. [3] or in a similar scale, also practically, by Xu et al. [4] and their heat exchange process is under investigation, e.g. by Guo et al. [5]. Settling chambers do not exist in collectors of heat exchangers in Ref. [1] and the calculations were performed as the unsteady ones. The presence of separated settling chambers introduced here affects the steady operation of heat exchangers. Settling chambers are widely used in analysis of flows, from sound pipes, as analysed at low speed by Erdem et al. [6], through cavitation effects in crossflows presented in Chemloul's paper [7], nozzle effects with entropy noise discussed in Leyko et al. [8], or sound generation in Kings et al. [9]. The heat exchange aspects with estimation of the Reynolds and Nusselt numbers are discussed in Wang et al. [10]. The supersonic wind tunnels and

turbine devices with settling chambers are of wide interest to many researchers – Bhoi and Suryanarayana [11] attempted to predict the pressure characteristics, Rajani et al. [12], discussed temperature effects in testing aerodynamic forces, Silva et al. established a model for the Reynolds number test, [13]. In Chong et al.'s paper [14], settling chambers play a significant role in achieving a quiet, low turbulent open jet blow downstream the wind tunnel.

The EHVE is a two-stroke engine equipped with two cylinders, an expander E and a compressor C. Both cylinders are situated between heat exchangers: a heater H and a cooler Cl. The engine, based on a typical design of the internal combustion type, is equipped with its typical crankshaft and oil lubrication system. The phase angle between the pistons E and C is equal to 180°, see Fig. 1. The principle of operation of the EHVE was presented in some papers, e.g. [1], therefore here only a short description is given below in Section 1.1.

The experimental investigations of the prototype of the EHVE in its initial version have been presented in Ref. [15]. The results have shown that the heat exchange was not sufficient during the phase when valves 1 and 3 were closed. This has resulted in a new concept to use the blowers B₁ and B₂, introduced in Ref. [1], but in a different way here. The new idea requires presence of settling chambers in order to make the heat exchange process stable and, thus, more effective in charging proper, ready heat exchangers. Such an idea

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Nomenclature

α	crankshaft angle [rad, deg]
α_A	heat transfer coefficient [W/m ² K]
A	surface of heat exchange area [m ²]
C_p	specific heat at constant pressure [J/kg K]
d	diameter [m]
D	cylinder diameter [m]
η	efficiency [%]
η_{PH}	efficiency with a pre-heater present [%]
L	mechanical work [J]
l	length of tubes [m]
λ	heat conductivity coefficient [W/m K]
$\dot{m}_i$	mass flow rate (mass stream) [kg/s]
M_v	mass transported through a valve [kg]
μ	dynamic viscosity [kg/m s]
n	number of tubes
p	pressure [Pa]
P	power [W, kW]
Pr	Prandtl number
Q	heat [J]
$\dot{Q}_A$	heat stream through the surface area [W]

Re	Reynolds number
s	stroke [m]
SC	settling chambers
T	temperature [K]
t_{pe}	period of engine work [s]
V	volume [m ³]

Subscripts

$B_1, B_2, B_{H1}, B_{H3}, B_{C12}, B_{C14}$	blowers
C	compressor
Cl	cooler
Cl_2, Cl_4	collectors of the cooler
CS	averaged compressor mass stream
E	expander
ES	averaged expander mass stream
f	friction
H	heater
H_1, H_3	collector of the heater
PH	pre-heater
wCL	cooler wall
wH	heater wall

allows one also not to include the blowers B_1 and B_2 into the new design.

Two new solutions are introduced here: the settling chambers – SC, 4 elements, and additional blowers, also 4 elements. They are inserted into the design in an obvious way. The separate settling chambers are new volumes and so are the blowers realizing the pressure drop in the exchangers. Some other possibilities are described in the next section, which is devoted to activities inside the heater and cooler volumes. In Ref. [16] a solution with two small heaters operating alternatively is described. The solution enables, however precisely acting of two distributors and a blower and it is not simpler than the one presented here.

1.1. Idea of the engine work

When the piston of the cylinder E starts to move down from its upper position, valves 1 open and the working gas at high temperature and pressure flows from the heater H to the expander

volume E, Fig. 2. Then, valves 1 close at about half of the height of the cylinder E and, further, the piston movement and expansion of the gas locked inside the expander volume takes place until the piston reaches its lowest position. At the same time a part of the working fluid locked in the volume of the cylinder C is compressed and prepared to be forced to enter into the heater volume. Valves 3 open when pressure in C reaches the level of the heater value. When the piston in C reaches its upper position, valves 3 close. Then both pistons in the cylinders E and C start their cycle again.

The expander piston moves up and valve 2 opens, allowing the overworked gas to enter the cooler. At the same time the piston in C moves down, valve 4 opens and cold air from the cooler flows to the cylinder C. Finally, the pistons reach their primary positions, valve 2 and 4 close and the cycle of the EHVE finishes. Valves 1 and 3 are doubled for better fillings of the cylinders E and C, Fig. 2.

2. Modelling of the heat exchanger operations

Our earlier results [1,2] suggest that the collectors of heat exchangers may play a role of settling chambers which take the highly unsteady gas stream incoming from the engine at one side and change it into an almost stationary stream at the other side (in fact, this can be an unsteady flow of rather insignificant changes). The change depends on the design and the volume of settling chambers, however, the algorithm applied in the model described in Ref. [1] does not take into account settling chambers and treats the flow in the collectors as an unsteady phenomenon.

The investigations of the behaviour and performance of the EHVE working under stationary conditions of its heat exchangers and a comparison to the non-stationary state is the main goal of the paper. The present paper does not describe how the settling chambers look like, only the basis for an assumption of almost stationary work of exchangers. A separation of collectors and settling chambers of both heat exchangers for different types of them is presented here in the configuration given in Fig. 2.

The settling chambers may be realized in a different way. For example, they may be linked with the collectors, but it needs some engineering invention and experimental verification. This is not a subject of this paper.

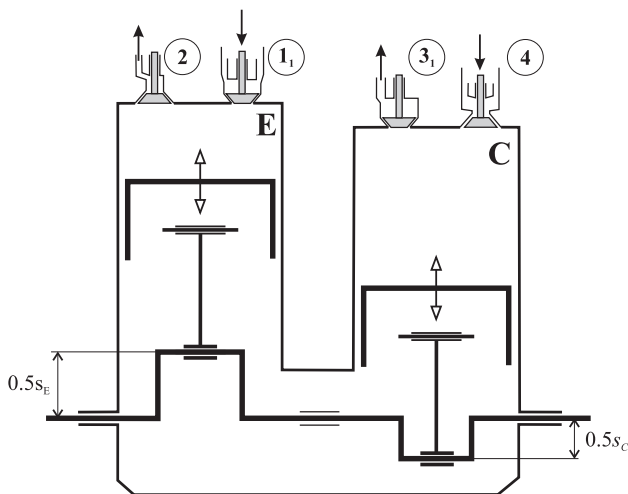


Fig. 1. Scheme of the longitudinal cross-section of the engine.

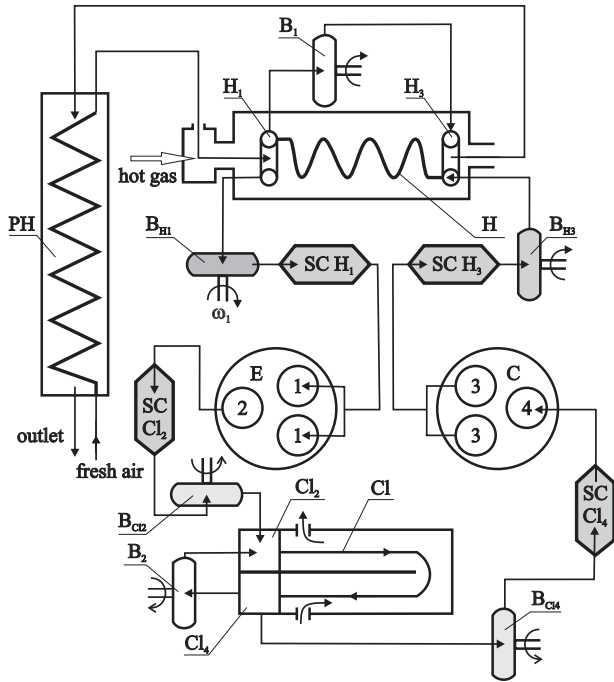


Fig. 2. Scheme of the EHVE engine: E – expander, C – compressor, H – heater, Cl – cooler, B₁, B₂, B_{H1}, B_{H3}, B_{CL2}, B_{CL4} – blowers, SC_{H1}, SC_{H3}, SC_{CL2}, SC_{CL4} – settling chambers, 1, 2, 3, 4 – valves, H₁, H₃ – heater collectors, Cl₂, Cl₄ – cooler collectors, PH – pre-heater. New elements changing the design with respect to [1] are marked in grey.

The next problem appearing for the EHVE is a pressure increase just upstream of the heater and the cooler – Δp_{H3} , Δp_{Cl2} and a decrease, Δp_{H1} , Δp_{Cl4} , respectively, downstream of the exchangers. The simulation program based on the algorithm published in Ref. [1] requires an assumption of values of Δp 's but does not determine how this could be attained. It may be executed by the blowers B_{H3}, B_{H1}, B_{CL2} and B_{CL4} as shown in Fig. 2, and this solution is discussed here. Other solutions are also possible, but they need some experimental verification.

Besides, in both earlier presented models there are two blowers B₁ and B₂ forcing the air transportation from both the collectors H₁ and Cl₄ to H₃ and Cl₂ volumes, respectively. The aim of application of these blowers is to intensify the heat exchange by an increase of the air stream, reflected by a value of the Reynolds number, through the exchangers. At the same time both the blowers B₁ and B₂ cause changes in temperatures inside the exchangers – an increase in the temperature T_{H3} instead of T_C^{max} and a decrease in T_{Cl2} instead of T_E^{min} , respectively (Fig. 3). This figure takes into account a new model of the EHVE with the settling chambers presented in detail in Section 4.

Two advantages are obtained by an application of the blowers B₁ and B₂: an increase in the mass stream flowing through the exchangers and a profitable change of the temperatures, Fig. 3. The troubles coming from their application and the necessary blowers B_{H3}, B_{H1}, B_{CL2} and B_{CL4} are such that they work with the same collectors, for example B₁ and B_{H3} are connected to the collector H₃, Fig. 2, etc. In such a case, in order to act parallel, the blowers should have similar characteristics. Using the settling chambers and all the blowers is intentional, this figure aims to explain operations of these elements in the EHVE.

Both the blowers B₁ and B₂ might be withdrawn when the settling chambers work as described above. It is connected with a decrease in the Re values in the exchangers and with a significant increase in the area of the heat exchange if the maximum

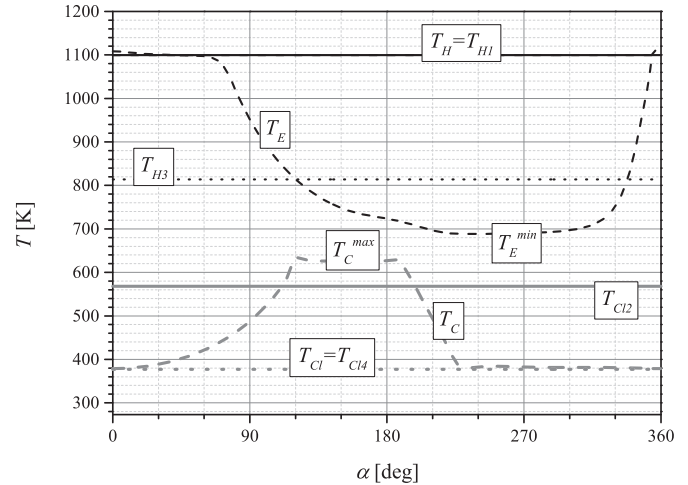


Fig. 3. Temperatures in the EHVE with the blowers B₁ and B₂ of the mass stream 0.1 kg/s.

temperature of the heated gas is close to that one when there are both blowers B₁ and B₂. A lack of B₁ and B₂ is attractive because only the blowers B_{H1}, B_{H3}, B_{CL2} and B_{CL4} remain and their characteristics do not need to be related to the B₁ and B₂ characteristics.

A new calculation model of the heat exchangers, where the settling chambers are separated, is presented in detail in Section 4, Fig. 2. The model of cylinders is not changed. The EHVE works in a closed cycle. It means that the amount of gas mass is constant throughout the whole cycle in the settling chambers. The period value of work of the engine and the heat exchangers depends on its rotation and is denoted as t_{pe} . An amount of the mass delivered or subtracted by a valve is M_v . Hence, at the steady side of the SC (Fig. 2), the mass stream is assumed to be constant:

$$\dot{m}_j = \frac{M_v}{t_{pe}} + \dot{m}_{Bi}, \quad (1)$$

where $\dot{m}_{Bi}$ ($i = 1, 2$) is a mass stream through the blower B₁ or B₂. In the case when either B₁ or B₂ does not exist, the mass stream $\dot{m}_j$ ($j = H, Cl$) decreases. The first part of the right hand side of Eq. (1) is explained exactly in Section 4 and marked in Eq. (13) as $\dot{m}_k$. How to calculate M_v will be explained later in this Section.

The gas flow through the exchangers is assumed to be always turbulent, i.e., $Re \geq 10^4$. A constant heat transfer coefficient is calculated for the outlet of the heater ($j = H$) as follows:

$$Re_H = \frac{4\dot{m}_H}{\pi d_H \mu_H n_H}, \quad (2)$$

$$Nu_H = 0.022(Re_H)^{0.8}(Pr_H)^{0.6}, \quad (3)$$

$$\alpha_{AH} = Nu_H \frac{\lambda_H}{d_H}. \quad (4)$$

The values of the working gas heat coefficients μ and λ are taken as averaged values in the temperature range in the exchangers from their inlet to the outlet. The heat stream delivered in the complete heater is determined by the formula:

$$\dot{Q}_{AH} = \alpha_{AH} A_H (T_{WH} - T_H), \quad (5)$$

where $A_H = \pi d_H l_H n_H$, $(T_{WH} - T_H)$ is a temperature difference between the heater wall T_{WH} and the gas inside its tubes T_H at the end

of the period of the EHVE. The difference ($T_{WH} - T_H$) is almost constant for the counter-current heat exchanger (for both, the heater and the cooler) modelled in the engine. T_{WH} and T_{WCL} are assumed at the outlet of air, similarly to [1].

For the new model in the collectors (Fig. 2), the density and the temperature are constant so the equations for the unsteady temperature obtained earlier transform to the equations determining the constant temperature in these collectors. The details of the calculations are given in Section 4. The temperatures T_{H3} and T_{H1} are calculated according to the new model (as well as the temperatures T_{Cl2} , and T_{Cl4}). It is proven in Section 4 that $T_{H1} = T_H$ and $T_{Cl4} = T_{Cl}$, so T_H and T_{Cl} can be determined. The temperatures T_H , T_{Cl} are determined (as before at the outlet of the heated air in H and in the outlet of the cooled air in Cl).

The heat exchangers work as stationary devices, so the temperature equation transforms to (e.g., for H):

$$C_{pH}\dot{m}_H(T_{H1} - T_{H3}) - \dot{Q}_{AH} = 0. \quad (6)$$

The $\dot{Q}_{AH}$ value from the above formula must remain the same as in Eq. (5). Similarly, $\dot{Q}_{ACl}$ are calculated and the two equations are obtained for the cooler. These equations are used for the additional determination of T_H and T_{Cl} , according to the new model.

Taking into account the above data, the heat stream for heat exchangers of the EHVE can be determined and it appears to be constant during the time t_{pe} .

3. Power and efficiency of the EHVE

The power and the efficiency estimated for the modelled EHVE is very important.

An amount of work created in the expander and the compressor can be calculated for a full cycle $0^\circ \leq \alpha \leq 360^\circ$, i.e., for the period t_{pe} , as:

$$L_E = \int_{\alpha=0^\circ}^{\alpha=360^\circ} p_E(\alpha) \frac{dV_E}{d\alpha} d\alpha, \quad (7a)$$

$$L_C = \int_{\alpha=0^\circ}^{\alpha=360^\circ} p_C(\alpha) \frac{dV_C}{d\alpha} d\alpha. \quad (7b)$$

The above pressure values are determined while taking into account losses in valves.

The work of the EHVE is a sum of:

$$L = L_E + L_C - \int_{j=1}^n L_{Bj} - L_f - L_{sup}, \quad (8)$$

where $\int_{j=1}^n L_{Bj}$ is the work of blowers and L_f is the work lost due to friction in the machine. L_{sup} denotes an amount of work lost in all additional devices attached to the engine. The blowers consume a

Table 1
Dimensions of the engine cylinders and the heat exchangers H and Cl, values of l_H and l_{Cl} vary according to formula (5) and results of calculations.

Cylinders	D_E	D_C	S_E	S_C
	0.0900	0.0900	0.0925	0.0694
Heater	d_H	n_H	V_{H3}	V_{H1}
	0.01	15	0.01	0.01
Cooler	d_{Cl}	n_{Cl}	V_{Cl2}	V_{Cl4}
	0.01	15	0.01	0.01

small amount of power if compared to that produced by the engine. The losses caused by the settling chambers have been also included (estimated at the level of 80 J–160 J).

A complete power output of the EHVE is determined as:

$$P = \frac{L}{t_{pe}}. \quad (9)$$

An amount of the heat delivered inside the heater is:

$$Q_H = \dot{Q}_{AH} t_{pe}. \quad (10)$$

The efficiency of the EHVE is defined by:

$$\eta = \frac{L}{Q_H},$$

$$\eta_{PH} = \frac{L}{Q_{H-PH}}. \quad (11)$$

The value of Q_H is calculated without an additional heat exchanger. However, the temperature of the gas heating the heater pipes at its outlet would be very high (Fig. 2), so a pre-heater (PH), may be applied. The pre-heater being an additional heat exchanger raises the inlet temperature of the heating gas and causes considerable savings in heat demand, decreasing the denominator value in Eq. (11) from Q_H to Q_{H-PH} .

4. Computer calculations

The calculations performed are a combination of the model described earlier in Ref. [1] and a new attempt. The results of calculations are very important, they are connected with the model used and given mainly in a graphical form. According to the idea, the following data have been assumed for the model: a constant output revolution speed of 1500 rpm, collector volumes of 10 L, the maximum cycle pressure in the EHVE – 100 bar, the heater wall temperature $T_{WH} = 1200$ K, the cooler wall temperature $T_{WCL} = 298$ K (both at their outlet). Other data are as in Table 1, except different values of A_H and A_{Cl} , depending on the fact if the B_1 and B_2 blowers exist or not. We average the results obtained for the data given in Table 1, from 0 to 360° for the heater and the cooler and for their collectors, i.e., the pressures p_H , p_{H1} , p_{H3} and p_{Cl} , p_{Cl2} , p_{Cl4} and also the temperatures T_H , T_{H1} , T_{H3} and T_{Cl} , T_{Cl2} , T_{Cl4} and this is the first step of a new model procedure.

For the cylinder E and valve 1, the mass of the working gas is then calculated – M_v . This represents an amount of mass circulating in the closed cycle of the EHVE engine. The settling chambers induce the averaged mass stream flows of constant values in both the cylinders, E and C, respectively:

$$\dot{m}_{ES} = \dot{m}_{CS} = \frac{M_v}{t_{pe}}, \quad (12)$$

where t_{pe} is the period of a cycle. The mass flow stream through the exchangers is constant:

$$\dot{m}_j = \dot{m}_k + \dot{m}_{Bi}, \quad (13)$$

where:

1. $k = ES, CS$ (the expander and the compressor averaged mass stream),
2. $j = H$ (with the collectors H1 and H3), or $j = Cl$ (with the collectors Cl2, Cl4),
3. $i = 1, 2$ for the blowers B1 and B2 (if they exist),

and the next steps of the new model calculation are explained below.

4.1. EHVE with settling chambers and the blowers B1 and B2

The considered exchanger collectors are those for the heater: $j = H$ (i.e., H1 and H3). We assume $\dot{m}_{H1} = \dot{m}_H$ in the collector H1. In such a stationary acting device, the balance of the mass streams is:

$$\dot{m}_H = \dot{m}_{ES} + \dot{m}_{B1}. \quad (14)$$

Just downstream of the collector H1 there is a settling chamber SCH1 taking the constant input mass stream flow. The SCH1 action causes the flow to become non-stationary at the other side of the settling chamber.

The equation allowing one to determine the temperature in the collector H1 comes from the equation for temperature for the collector H1 used in Ref. [1]:

$$\dot{m}_H T_H - \dot{m}_{ES} T_{H1} - \dot{m}_{B1} T_{H1} = 0. \quad (15)$$

From the above, $T_H = T_{H1}$ (see Fig. 3).

For the collector H3, we assume $\dot{m}_{H3} = \dot{m}_H$. The balance equation for the mass streams involved in the stationary collector H3 is:

$$\dot{m}_H = \dot{m}_{CS} + \dot{m}_{B1}. \quad (16)$$

The settling chamber SC_{H3} is located just downstream of valve 3 of the EHVE and the temperature at the end of this chamber is assumed constant under stable working conditions. The temperature marked as $T_C^{\max}$ occurs when the compressor C loads the working gas into the heater. For the calculation purposes, it has been based on the simulations of the compressor and the exchangers.

The equation of temperature conservation allowing one to determine the temperature in the collector H3 also comes from Ref. [1] and takes the form:

$$\dot{m}_{CS} T_C^{\max} + \dot{m}_{B1} T_{H1} - \dot{m}_H T_{H3} = 0. \quad (17)$$

$T_H = T_{H1}$ is taken from the further calculations – Eq. (21).

For the collectors of the cooler exchangers, an attempt of solution is similar. Now, $j = Cl$ (Cl2 and Cl4). For the collector Cl4, we assume $\dot{m}_{Cl} = \dot{m}_{Cl4}$. The mass stream balance gives:

$$\dot{m}_{Cl} = \dot{m}_{CS} + \dot{m}_{B2}. \quad (18)$$

From the temperature equation for the Cl4 collector, it results that $T_{Cl} = T_{Cl4}$.

For the collector Cl2, we assume $\dot{m}_{Cl} = \dot{m}_{Cl2}$. The mass stream balance gives:

$$\dot{m}_{Cl} = \dot{m}_{ES} + \dot{m}_{B2}. \quad (19)$$

The equation allowing one to determine the temperature T_{Cl2} is:

$$\dot{m}_{ES} T_E^{\min} + \dot{m}_{B2} T_{Cl4} - \dot{m}_{Cl} T_{Cl2} = 0. \quad (20)$$

We calculate T_{Cl2} from (20) but the temperature $T_E^{\min}$ needs some discussion. It is assumed as the temperature representing the output from the cylinder E to the cooler. We determine its value from simulations for the expander and the exchangers. This represents the temperature of the stationary side in the SC_{Cl2} volume, Fig. 2. $T_{Cl} = T_{Cl4}$ is taken from the further calculations – Eq. (22).

This concludes the calculations of temperatures in the collectors of the EHVE resulting from the equations for H1, H3, Cl2 and Cl4.

Now, let us check what values of temperatures result for the heater and the cooler, i.e., T_H and T_{Cl} at their outlets. The heat streams causing differences in temperatures in the exchangers

must be the same as the streams resulting from the calculations of the heat exchanged inside the whole exchanger pipes. For the heater, there is an equality of Eqs. (5) and (6), i.e.:

$$\alpha_{AH} A_H (T_{WH} - T_H) = C_{pH} \dot{m}_H (T_H - T_{H3}). \quad (21)$$

We are able to calculate T_H from Eq. (21). The gas coefficients C_{pH} , μ_H , λ_H are taken as averaged values between the heater collectors. Besides, $A_H = 1.2 \text{ m}^2$. The results of these calculations for H are given in Fig. 3.

For the cooler, we have the following equation:

$$\alpha_{ACl} A_{Cl} (T_{wCl} - T_{Cl}) = C_{pCl} \dot{m}_{Cl} (T_{Cl} - T_{Cl2}). \quad (22)$$

From Eq. (22), we calculate T_{Cl} . The gas coefficients C_{pCl} , μ_{Cl} , λ_{Cl} are taken as averaged values between the cooler collectors. Besides, $A_{Cl} = 1.0 \text{ m}^2$. The results of calculations for CL are also given in Fig. 3.

4.2. EHVE with settling chambers and without the blowers B1 and B2

The settling chambers act as described in the Introduction. All the assumptions listed at the beginning of this Section are also held. In the considered case, $\dot{m}_{Bi} = 0$ and the value of Re in the exchangers diminishes significantly due to the fact that $\dot{m}_j$, $j = H, Cl$ is lower. It is now, according to (1) and (12)–(13), equal to $\dot{m}_{ES} = \dot{m}_{CS}$. An advantage of this solution is an easy choice of the blowers B_{H1} , B_{H3} , B_{Cl2} , B_{Cl4} characteristics.

In order to obtain similar power of the engine as with the blowers B_1 and B_2 there is a need to increase the area of the heat exchange. Considering the presence of collectors in the heater and in the cooler, we arrive at somehow obvious results: $T_H = T_{H1}$, $T_{H3} = T_C^{\max}$, $T_{Cl} = T_{Cl4}$ and $T_{Cl2} = T_E^{\min}$ – see Fig. 4. In this case, we need to calculate the values of T_H and T_{Cl} when the condition of equality of heat streams calculated on the basis of changes in temperatures from the inlet to the exchanger to its outlet and the stream delivered in the exchanger pipes holds.

For the heater, this equality is described by the equation:

$$\alpha_{AH} A_H (T_{WH} - T_H) = C_{pH} \dot{m}_H (T_H - T_C^{\max}). \quad (23)$$

We can calculate T_H from Eq. (23). The gas coefficients C_{pH} , μ_H , λ_H are taken as averaged values between the heater collectors. Besides, $A_H = 1.74 \text{ m}^2$. The results are given in the form of Fig. 4.

For the cooler, the equation of equality is as follows:

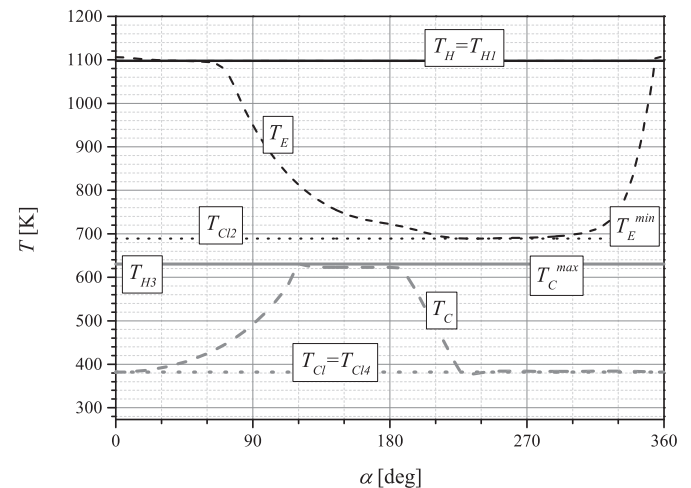


Fig. 4. Temperatures in the EHVE without the blowers B_1 and B_2 .

$$\alpha_{\text{Cl}} A_{\text{Cl}} (T_{\text{wCl}} - T_{\text{Cl}}) = C_{\text{pCl}} \dot{m}_{\text{Cl}} (T_{\text{Cl}} - T_{\text{E}}^{\text{min}}). \quad (24)$$

We can calculate T_{Cl} from Eq. (24). The gas coefficients C_{pCl} , μ_{Cl} , λ_{Cl} are taken as averaged values between the cooler collectors. Besides, $A_{\text{Cl}} = 1.46 \text{ m}^2$. The results of calculations are given in Fig. 4.

4.3. Calculation of the power and the efficiency

According to the earlier discussion in Sections 2 and 3, the losses have been calculated with all attachments included and the settling chambers. The existence of a pre-heater is included in the calculations at the stage of efficiency estimation through diminishing the gas heat stream delivered by 15%. When both the blowers B_1 and B_2 exist, the gas flow transported through them is $\dot{m}_{B_i} = 0.1 \text{ kg/s}$ and when they are not included in the working gas path, then $\dot{m}_{B_i} = 0.0 \text{ kg/s}$, which can be seen in Fig. 5. The existence of the settling chambers and their additional blowers causes losses which have been estimated from 80 to 160 J. They have to be included in the calculation of the power and the efficiency of the EHVE with settling chambers. In the calculation algorithm, the initial phase has been performed similarly to the procedure described in Ref. [2] until the stable state is reached (typically 250 cycles) and, later, a new procedure replaces the action of the heat exchangers while the main part of the engine is simulated normally, like in Section 4. The new procedure includes additional losses caused by the settling chambers and the results can be seen in Figs. 5 and 6. Fig. 6 shows the power and the efficiency of the EHVE depending on the losses caused by the installed settling chambers and blowers.

5. Conclusions

The discussed air engine with external heating and with separate settling chambers coming apart from the collectors and the additional blowers which operates as described in Ref. [1] has been analysed in the paper. The scheme shown in Fig. 2 is more complicated if compared to the previous solution, but gives an advantage of steady action of both heat exchangers. A simulation model is a combination of the model presented for unsteady flows and a new idea described in Sections 2 and 4. The applied solutions are obvious but reliable. Other solutions are possible, but they need rather costly experiments.

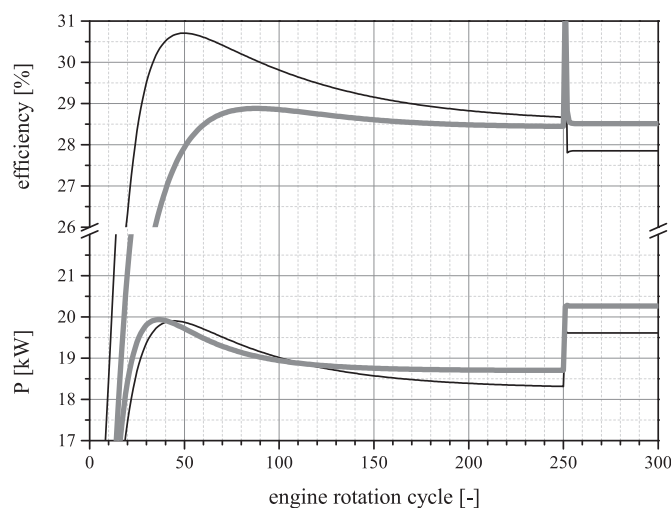


Fig. 5. Power (bottom) and efficiency (top) of the EHVE when losses in the settling chambers have been assumed at the level of 3000 W. Thin, black lines – without blowers and thick, gray lines – with blowers. The new model simulation results after 250 cycles. The mass stream through both blowers, B_1 and B_2 , at 0.1 kg/s.

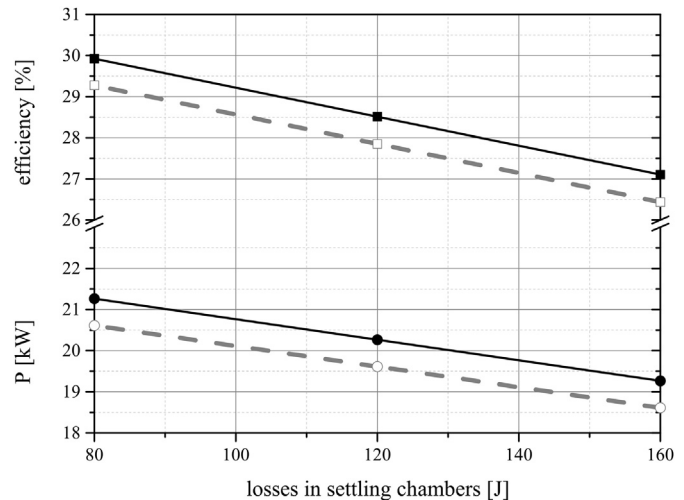


Fig. 6. Power and efficiency of the EHVE as a function of losses in the settling chambers. Rectangles – efficiency in [%] and circles – power in [kW]; Dashed lines and open symbols – without blowers; continuous lines and filled symbols – with blowers. The mass stream through both blowers, B_1 and B_2 , at 0.1 kg/s.

An application of the blowers B_1 and B_2 yields double advantages: it intensifies the velocity of the working gas flow through the heat exchangers and provides a profitable character of the temperature changes inside the collectors H3 and Cl2, see Fig. 3. The disadvantage of such a solution lies in a specific choice of their characteristics which has to remain in coexistence with the power characteristics of the blowers B_{H1} , B_{H3} , B_{Cl2} and B_{Cl4} . The latter complication may be avoided when the blowers B_1 and B_2 are withdrawn but the settling chambers are still applied.

It causes a significant diminish of the working gas speed inside the heat exchangers. In order to reach a similar amount of power and efficiency as that one obtained with the B_1 and B_2 blowers only, there is a need for a significant increase in the area of the heat exchange in both the heater and the cooler, respectively.

An application of the settling chambers and the blowers at the heat exchangers involves additional losses of the working gas energy. It has been assumed to vary, depending on the design of the settling chambers, from 80 J to 160 J. The power and the efficiency of the EHVE with separate settling chambers for different levels of losses inside them, with and without the blowers B_1 and B_2 , are described.

The subject presented here is a new solution for the air engine with external heating with separated settling chambers applied. The results of simulations of the present design for the engine parameters described in Table 1 with a reasonable amount of losses present similar values of power and efficiency not less than the averaged values in the non-steady solution, but now the heat exchange becomes a stationary process. This new idea may seem interesting for the world energy community.

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